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Iogenic Plasma and its Rotation-Driven Transport in Jupiter's Magnetosphere

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I. Introduction

In this project, research is focused upon studies for the heavy-ion-dominated plasma torus (O^+, O^{++}, S^+, S^{++}, S^{+++}, S^{++++}) and its near plasma sheet extension produced by the ionization of O, S, SO, and SO_2 gases from Io. Specifically, we will undertake explicit studies and calculations to describe the Iogenic plasma source and to establish its outward rotation-driven transport pattern in Jupiter's magnetosphere in order to identify and understand the space plasma phenomena that shape it into the Io plasma torus. This will be accomplished by combining state-of-the-art calculations at AER for the internal Iogenic plasma source and numerical solutions of the nonlinear transport equations in a collaborative effort with R. A. Wolf and colleagues at Rice University using the Rice Convection Model for Jupiter (RCM-J). In this way we will address the complex plasma torus structures that emerge from the source and transport processes.

The RCM-J's use of a fine two-dimensional grid and its many-fluid representations of the plasma make it more capable of representing this complex region than any other existing computational framework of which we are aware. The calculation of a continuous/spacetime-dependent Iogenic plasma source in three-dimensions for a number of different Io gas-loss scenarios and its proper interface with the RCM-J provide a critical and presently missing element for this convection model. The Iogenic plasma source model is quite sophisticated and contains, for example, east-west and System III longitudinal asymmetries in the spacetime description of the plasma torus. The many different observational data that are carefully crafted together in determining the nature of the Iogenic plasma source will bring a required reality to this convection model that is necessary to unravel the structure and transport physics of the plasma torus. The natural processes involved in the transport are to be systematically studied one by one. Therefore, numerical simulations are intended both to clarify the conditions for validity of various theoretical scenarios and to provide a useful tool for interpretation of plasma torus structures and *in situ* and remote data acquired by Galileo.

II. Summary of Work Performed in the Second Quarterly Period

Research work in the second quarterly period has been minimal since major efforts have been scheduled for the second half of the first project year, as noted in the first quarterly report. However, some refinements were made in the neutral cloud model in preparation for calculation of the Iogenic plasma source to be undertaken later in the year. These refinements are described below.

In calculating the Iogenic plasma source rates (i.e., the net ion-loading rate, net mass-loading rate, equivalent mass loading-rate for momentum loading, and energy-loading rate), it is important to understand the relationship between the instantaneous neutral source rate at Io, the neutral cloud instantaneous accumulation rate in the circumplanetary environment, and the instantaneous loss rates of neutrals in the magnetosphere, the latter of which produces the Iogenic plasma source. The relationship among these three quantities has been derived mathematically using the general "ensemble packet" formalism developed by Smyth and Combi (1988). The results are presented briefly below.

Consider on Io's exobase a solid angle element $d\Omega$ at the location $\hat{\Omega}$ and atoms ejected from this element with a velocity in the range $\bar{\omega}$ to $\bar{\omega} + d\bar{\omega}$. We denote the neutral source rate (atoms per second) originating with the conditions $(\bar{\omega}, \hat{\Omega})$ at time T by $\phi(\bar{\omega}, \hat{\Omega}, T)\, d\bar{\omega}\, d\Omega$ where $\phi(\bar{\omega}, \hat{\Omega}, T)$ is the flux per unit $d\Omega$ and per unit $d\bar{\omega}$. We denote by $N(\bar{\omega}, \hat{\Omega}, T)\, d\bar{\omega}\, d\Omega$ the number of neutrals at time T along the complete neutral trajectory formed prior to the time T and originating with the conditions $(\bar{\omega}, \hat{\Omega})$. We furthermore denote the neutral cloud instantaneous accumulation rate at time T for atoms originating with the conditions $(\bar{\omega}, \hat{\Omega})$ for past times up to time T by

$$\frac{dN(\bar{\omega}, \hat{\Omega}, T)}{dT}\, d\bar{\omega}\, d\Omega. \tag{1}$$

Finally, we denote by $L(\bar{\omega}, \hat{\Omega}, T)\, d\bar{\omega}\, d\Omega$ the instantaneous neutral cloud loss rate at time T caused by magnetospheric processes for the complete trajectory originating with the conditions $(\bar{\omega}, \hat{\Omega})$. The desired relationship may then be expressed as follows

$$\phi(\bar{\omega}, \hat{\Omega}, T) - \phi^{(\mathrm{exit})}(\bar{\omega}, \hat{\Omega}, T) = \frac{dN(\bar{\omega}, \hat{\Omega}, T)}{dT} + L(\bar{\omega}, \hat{\Omega}, T) \tag{2}$$

where $\phi^{(\mathrm{exit})}(\bar{\omega}, \hat{\Omega}, T)$ is the instantaneous atom flux along the trajectory that is lost from the trajectory because of collision with Io, collision with Jupiter, or that remains undepleted and unchanged on the trajectory having been ejected from Io at times prior to time T.

The equation (2) is a conservation statement at time T for the complete trajectory originating with the conditions $(\bar{\omega}, \hat{\Omega})$. The left hand side is the instantaneous net flux at time T from Io that is available to either increase the neutral cloud abundance along the entire trajectory or to supply the neutral cloud loss rate caused by the magnetospheric processes. Note that this neutral cloud loss rate may be smaller than the net flux if the abundance of neutrals along the trajectory is increasing or may be larger than the net flux if the abundance of neutrals along the trajectory is decreasing. Hence the neutral cloud is a reservoir for the neutrals that can increase in abundance when the global loss rate becomes smaller and can decrease in abundance when the global loss rate becomes larger. The time variability in the loss rate is caused by the oscillation of the plasma torus about Io's orbital plane, the System III longitude asymmetries of the plasma torus, and the east-west asymmetries of the plasma torus.

In the past quarter, the neutral cloud model was modified to include the calculation of the rate of change of the neutral cloud abundance, the first term on the right hand side of equation (2). Care had to be taken in the implementation since the code uses variable time steps. For the atomic oxygen and atomic sulfur neutral cloud models, the code was verified for various individual orbits originating from the exobase.

REFERENCES

Smyth, W. H., and Combi, M. R. (1988) A General Model for Io's Neutral Gas Cloud. I. Mathematical Description. Ap. J. Supp. 66, 397-411.

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The relationship between the instantaneous neutral source rate at Io, the neutral cloud instantaneous accumulation rate, and the instantaneous loss rate of neutrals in the magnetosphere is formulated and discussed. These three quantities provide a conservation equation for the neutrals, where the latter quantity produces the Iogenic plasma source of interest to this project. Refinements were implemented in the neutral cloud model to calculate all elements of this conservation equation.

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